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THE USE OF GEOTHERMAL ENERGY AT MILITARY INSTALLATIONS.(U)

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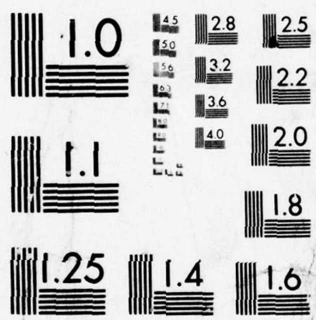
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A Research Report

The Use of Geothermal Energy at Military Installations

by
W. R. McSpadden

October 1976

Prepared for Defense Advanced Research Projects Agency Energy and Resources Program

BNW Contract No. 2311103035
BCL Contract No. G-1731-2157
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1. OVERALL GEOTHERMAL PROGRAM

1.1 CURRENT STATUS OF GEOTHERMAL ENERGY DEVELOPMENT

Geothermal energy, the natural heat of the earth, which comes from decay of radioactive materials in the earth's crust, is trapped within the earth and can be utilized by man. Temperatures in the earth increase with depth at a world average of approximately 25°C/km but vary greatly at local hot spots. At the base of the continental crust (25 to 50 km), temperatures range from 400 to 1200°C and increase to perhaps 4500°C at the center of the earth.

Although this energy resource is essentially unlimited, most of it is located too deep to be economically extracted with current drilling technology . Drilling can reach a depth of approximately 10 km and may some day reach 20 km. However, many geothermal resources are near the earth's surface and can be economically extracted.

Recent assessment of geothermal resources in the United States (White and Williams, 1975) estimates that 46,000 MW-centuries of geothermal energy is available with current technology from hydrothermal convection systems, and an additional 34,000 MW-centuries of energy is recoverable from geopressured systems within the U.S. Geothermal energy has been tapped for electric power generation since 1904, although only recently has there been any rapid expansion and development. Current world-wide power generation is 1420 MWe from a total of seven nations. The U.S. has only one producing field, The Geysers, which is the largest producer of geothermal electric power (520 MW). An even larger energy resource is available from lower temperature geothermal fluids that can be used for space heating, agriculture, and industrial processes. Geothermal resources can ultimately produce 5 to 10% of the nation's energy needs and ERDA has a current national goal to develop 20,000 MW of power by 1985.

Development of the geothermal resources can be categorized as follows: exploration and discovery of resources, energy extraction, consumer utilization, environmental engineering, and control of chemical properties of fluids. Research and development is currently underway in all of these areas with FY77 budgets of: ERDA - $84.7 million, USGS - $9.4 million. The breakdown of the ERDA geothermal budget is:

FY77 ERDA Budget	($ thousands)
Engineering R&D	$13,500
Resource Exploration and Assessment	9,000
Hydrothermal Systems	14,000
Advanced Technology Applications	11,900
Environmental and Institutional Studies	4,800
Capital Equipment	1,500
Loan Program	30,000
Total FY77 Budget	$84,700

As of FY76, there were approximately 73 projects being funded by ERDA's Geothermal Energy Division with the projects distributed approximately in proportion to the above budget request.

The primary legislation most pertinent for the development of geothermal energy is contained in three Acts. The first of these was the Geothermal Steam Act of 1970 (30 USC 1001-25), effective December 24, 1970. This Act authorizes the Secretary of the Interior to lease Federal lands for geothermal resource exploration and development and production of energy as well as useful by-products. The Department of the Interior, through the Bureau of Land Management and the U.S. Geological Survey, conducts the Federal leasing program which is under the Act's authority.

The second legislative act, the Geothermal Energy Research and Development and Demonstration Act of 1974 (Public Law 93-410), was enacted on September 3, 1974. The Act establishes responsibility for effectively managing and coordinating a national geothermal resources program to include:

- evaluating the resource base determination
- research and development for exploration, extraction and utilization technologies
- demonstrating appropriate technologies, and
- development of a loan guarantee program.

The third piece of legislation was the Reorganization Act of 1974 (Public Law 93-438) enacted on October 11, 1974. It established ERDA which includes an Administrator, a Deputy Administrator and six Assistant Administrators, one of whom is responsible for solar, geothermal and advanced energy systems. ERDA has the responsibility of bringing together and directing Federal activities relating to research and development of all energy sources, including geothermal.

1.2 THE ARPA RESEARCH PROGRAM

Development of geothermal energy is part of the ARPA Energy Resource Program for the total development of energy systems for military installations. An energy model developed by Stanford Research Institute for ARPA provides the means for evaluating the technical and economic feasibility of all energy sources to supply the energy needs of military installations. The model has been used to study potential geothermal energy systems. The results indicate that the costs of installing and operating a geothermal energy system appear to be competitive with fossil fuel systems. Further study shows that at thirty-six military installations in CONUS and ten U.S. sites outside of CONUS geothermal sources exist either on or nearby the military installations (Combs, 1973; Schmidt, 1972).

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This report is a result of the review of eight ARPA funded projects to a) identify (1) geothermal resources for military installations and ~~b) identify~~ (2)

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key problems for their development. Of these, four projects dealt with identification and evaluation of resources (Combs, 1973; Combs, 1975; Combs, 1976; and Herrin, 1973). Two dealt with problems associated with the chemistry of geothermal fluids, in particular corrosion and scaling (Austin and Pringle, 1974, and Finnegan, 1976). One project was concerned with the critical problem of drilling for geothermal resources (Patterson, Sabels, Kooharian, 1973) and one was a review of the current state-of-the-art of geothermal energy development (Stevovich, 1975).

As a result of these studies, two target areas have been identified as prime candidates for development of geothermal energy at military installations. The Coso Hot Springs, on the Naval Weapons Center at China Lake, CA, and the Marine Corps base at Twenty-nine Palms, CA. In addition, two test sites are proposed in southern Texas for research and development of geopressured systems (Combs, 1973; Herrin, 1973).

As of the beginning of FY77, the Coso Geothermal Site is under active exploration and development with research funding from ERDA. This project is budgeted at $1.3 million for Battelle, Pacific Northwest Laboratories (BNW), the prime contractor, plus $150,000 to the Naval Weapons Center for logistics and environmental support of the project. It is anticipated that two exploration wells to approximately 4000 ft will be drilled during FY77 as the first in-depth probe of the geothermal resource (Combs, 1976).

The objectives of these eight ARPA funded research projects have been accomplished in that they have a) successfully identified military installations where geothermal resources are known to exist and can be developed, b) they have identified key problems that must be solved before development can take place, and c) joint research projects with ERDA and USGS are now taking place to develop these national resources.

2. SCIENTIFIC AND TECHNICAL RESULTS

2.1 NONELECTRIC GEOTHERMAL APPLICATION

Most of the literature and recent research associated with the geothermal industry has been devoted to the generation of electric power, but the most significant geothermal applications will probably be in the nonpower generation sector. Unlike most other applications, electric power generation uses geothermal energy at an efficiency of only 10 to 20%. As of 1975, nonelectric applications use approximately 6600 MW (thermal) compared with electric power generation which uses a world total of 3600 MW (electrical).

The breakdown of geothermal consumption by countries is shown in Table 1 with Russia leading the field (5100 MW). Most of this energy in Russia is used in agriculture where over one million tons of vegtables are produced each year. Russia also has significant space heating and refrigeration applications. Both Hungary and Iceland use geothermal hot water to heat homes and commercial buildings. New Zealand leads in industrial applications with over 100 MW (thermal) being used in the pulp and paper mills near their Kawerau electric power plant. These countries and others have utilized geothermal fluids for recreational and health purposes, such as health spas and swimming pools. Use of geothermal energy in these nonelectric applications--space heating and refrigeration, industrial processing, agriculture, and recreational and health purposes--will continue to exceed the applications in electric power generation, primarily because geothermal reservoirs tend to be of lower temperature.

Stevovich, 1975, has displayed the nonelectric applications as a function of temperature in Figure 1. This figure also illustrates the diversity of applications, most of which will become more important as the cost of fossil fuels continues to rise. Certainly in the U.S. applications have been limited by the availability of inexpensive fossil fuels, as well as a lack of geothermal technology. Other factors, such as availability of markets and transportation problems to and from geothermal sources, must also be considered.

TABLE 1. Nonelectric Applications of Geothermal Energy

Country	Total Use (1975) (MW_t)	Space Heating & Refrigeration	Food and Industrial Processing	Agriculture	Recreational and Health	Comments
Russia	5100	✓	✓	✓	✓	Russia started a national program in 1920 and is completing an additional 10,000 m of new test wells. Over 10^6 T/yr of vegetables are produced.
Hungary	770	✓		✓	✓	131 wells provide district heating for 20,000 residents of Budapest and other cities. Animal husbandry and facilities heating are primary uses.
Iceland	590	✓	✓		✓	About 127,000 Icelanders' homes are heated from geothermal sources
New Zealand	100		✓		✓	The Tasman Pulp and Paper Mill at Kawerau uses geothermal process heat.
United States	16	✓			✓	Boise uses about 9 MW_t and Klamath Falls about 5 MW_t for residential space heating.
TOTAL	6576					

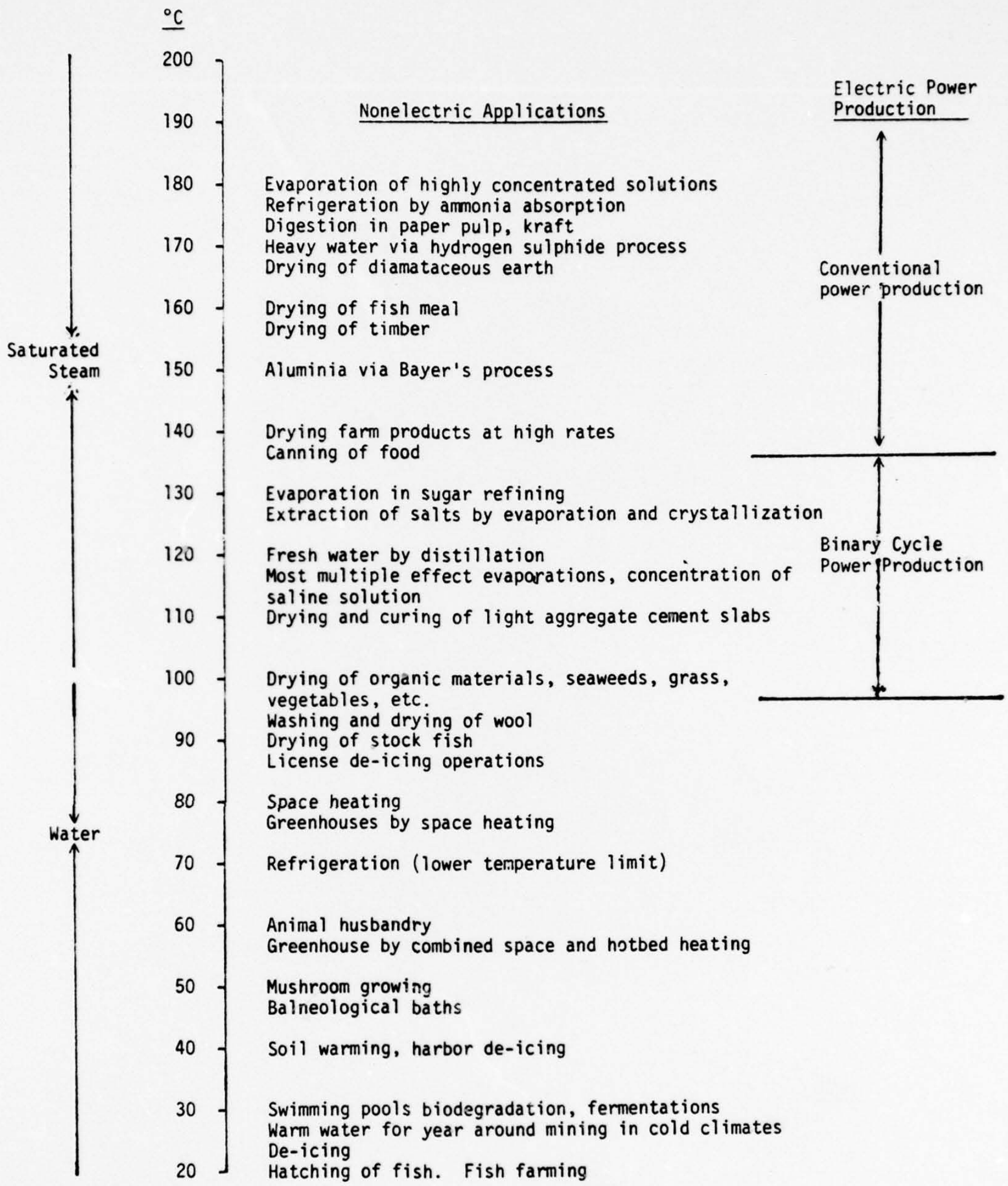


FIGURE 1. Geothermal Applications as a Function of Temperature.
Source: V. A. Stevovich, 1975

Space Heating and Refrigeration

One of the most obvious and principal applications of geothermal fluids is in the direct heating of homes and buildings which uses fluids at temperatures as low as 50°C. In cases where geothermal fluids are relatively pure water they may be piped directly through the heating system and reinjected or used for other purposes. Iceland has such relatively pure geothermal fluids and has been heating residences for 127,000 inhabitants by this means.

For highly mineralized thermal waters, a centrifugal separator or a flash chamber may generate steam to transmit through the heating system. Corrosive and mineralized fluids may require heat exchangers. Here, relatively pure water is used on the secondary side of the heat exchanger for transmission through the utility system and the geothermal fluids on the primary side of the heat exchanger are reinjected into the geothermal reservoir.

The principal noncondensible gases in geothermal fluids are carbon dioxide and hydrogen sulfide, whose disposal can become an economic problem. Geothermal fluids used for space heating should have the noncondensible gases removed without the addition of oxygen. They should have a relatively neutral pH with less than 700 mg/liter carbonate residuals (hardness indicator) and less than 5 mg/liter sediments.

It is believed that industrial and commercial applications must be located near the geothermal reservoir. However, Einarsson, 1973, discusses several installations where water at less than 100°C is piped distances up to 20 km before utilization. He also states that 180°C water could be transmitted as far as 75 km. With the technology being developed in the oil industry for transmission of fluids great distances through arctic wastelands, the technology is apparently available for long distance transmission of geothermal fluids.

Department of Defense installations may have a particular advantage to develop low cost geothermal heating sources because military bases essentially function as controlled communities. Since hot water sources are very widely distributed, many DOD sites have the potential for direct utilization

of geothermal fluid for heating and refrigeration (Combs, 1973). Besides the economics in conservation of fossil fuels, utilization of geothermal sources at remote DOD sites offers a potential advantage of some independence of oil supply lines. This may be particularly valuable for arctic sites where access is limited by weather conditions.

Air conditioning can be accomplished with cool geothermal waters (less than 15°C) by direct circulation. Also, heat pumps can be used effectively for both heating and cooling, using geothermal fluid as the heat source or sink. Heat pumps are now commercially available in most industrial countries and are becoming more and more competitive economically. To obtain industrial refrigeration with temperatures below 0°C, ammonia-water refrigeration units have been used, but geothermal fluids of fairly high temperatures (about 175°C) are required for effective operation. For temperatures above 0°C lithium-bromide machines are available which require geothermal fluid temperatures of only about 70°C. The lithium-bromide refrigeration units are being manufactured on a routine basis in Russia to meet the great demand for refrigeration in the chemical industries. Although the Russians probably lead in the field of application of absorption refrigeration, an interesting installation of geothermal heating and air conditioning exists at the Rotorua International Hotel, New Zealand. The system is designed for the extreme climatic temperatures from -4°C to +30°C. A 130-ton (0.39 Gcal/h) lithium-bromide absorption unit requires a heat input of 0.575 Gcal/h. The specific energy requirement of the absorption unit is therefore 1.47 kcal/h per 1 kcal of cooling. The Russian industrial units are approximately 5 times the capacity of this refrigeration unit, (Stevovich, 1975).

Industrial Processes

There is almost an endless variety of industrial processes that use various forms of heating, drying, distillation, refrigeration and air conditioning. Many of these energy consumption processes are driven from electrical sources or from fossil fuel. As the cost of these sources of energy increases, geothermal fluids become a more attractive competitor.

One of the largest applications occurs at the Kawerau geothermal field in New Zealand where approximately 100 MW of thermal power is supplied to the nearby Tasman Pulp and Paper Company who operate mills to produce newsprint, kraft pulp and sawn timber.

Effective methods for evaluating potential applications were advocated by Lindal, 1973, at the conference in Pisa. His proposed index is the ratio of the pounds of steam required to produce a unit dollar value of the end product. For many products, such as the production of heavy water via the hydrogen-sulphide process, and for sea water desalination, the index is very high. However, the index is low for many chemical processes, such as the production of ammonium-sulphate and ammonium-nitrate, and the preparation of acetic acid from the Othmer process.

Chemical by-products from the geothermal waters provide another potential application and source of raw materials. Frequently, hot geothermal waters contain large amounts of salt, iodine, bromine, naphthenic acid, boron, strontium, lithium, fluorine and other rare elements.which can easily be extracted. Many of the trace elements and rare metals increase in concentration with depth of the geothermal waters, while boron and iodine show a reverse tendency. In addition, CO_2 and H_2S, the primary noncondensible gases, can be extracted for commercial use. Wells were drilled in the Salton Sea area as early as 1927, and dry ice was produced there commercially for several decades. The geothermal fluids of the Salton Sea are so saline (200,000 to 300,000 ppm total dissolved solids) that a 250 MW plant would have an annual production of potassium chloride greater than 4 million tons. The lithium and cesium of the brine from such a plant probably would exceed the known world reserves. An exploratory well was recently drilled in the Kashkaderinsk Artesian Basin in Russia which produced 2700 tons of potassium chloride, 9 tons of bromine, and approximately 220 lb of iodine in the first year. Soviets recently announced development of techniques for extraction of boron, alkali, and alkali earth metals from geothermal fluids. At the power plant at Larderello, Italy, noncondensible gases were collected to produce boric acid, ammonium bicarbonate, ammonium sulphate and sulphur, although this apparently has not been done in recent years (Stevovich, 1975).

The separation of heavy water from ordinary water is a high energy consuming process which can be accomplished with geothermal steam with a 10 to 15% cost reduction over conventional sources. Thus the manufacture of heavy water (D_2O) by the H_2S/H_2O ion exchange method with geothermal heat appears quite promising.

In northern climates geothermal fluids have a potential application for the de-icing of air fields, roads, sidewalks and harbors. Relatively low temperature waters can be used for many of these applications, including discharge waters from power plants or chemical processing industries.

Agriculture

Agriculture use of geothermal fluids is not new, but the incentive for new development increases as the cost of fossil fuel increases. Potential applications for agriculture are very large, particularly in the less industralized countries. It has been estimated that 5 acres of heated soil would produce year-round vegetables for a population of 20,000. Geothermal fluid temperatures of 30°C are appropriate for soil heating and temperatures of 50 to 60°C for hot houses. Perhaps the tremendous potential for agriculture use is best indicated by field experiments that were conducted in 1969 near Corvallis, Oregon to measure the effects of soil warming. The yield of corn increased by 45%, tomatos by 50%, soybeans by 66% and beans by 39% (Stevovich, 1975).

2.2 ELECTRIC POWER GENERATION FROM HYDROTHERMAL SYSTEMS

The generation of electric power from geothermal steam first began in Italy in 1904 from the Larderello Field where dry steam issues from vents in the earth. Continuous operation and growth have occurred at Larderello since that time and production is now approximately 420 MW. However, Larderello Field appears to have reached its maximum potential since reservoir pressures have been dropping as recent wells have been added. Because fossil fuels were so inexpensive during the first half of the 20th century the development of other geothermal fields did not receive serious attention

until the 1950s and 1960s. The 1975 status of electric power production by geothermal sources is shown in Table 2. As of 1975, seven nations were producing a total of 1420 MW of power from geothermal sources. The countries are listed in Table 2 in order of the quantity of power produced. Although the United States is first on the list with 520 MW, it has only one field, The Geysers, where power production is actually taking place.

Geothermal power plants can be somewhat arbitrarily classified according to the nature of the geothermal source. The five basic types of geothermal reservoirs listed in the order of the ease of development of electric power are:

1. Vapor-dominated, where steam but little or no water comes to the surface.
2. Flashed steam where water and steam must be separated at the surface.
3. Hot water, not flashed (binary cycle).
4. Geopressured reservoirs where both thermal and mechanical energy can be utilized.
5. Dry hot rock where water must be injected to obtain steam.

The largest and most successful fields have been of the dry steam type as exemplified by The Geyers and the Larderello Fields. Flashed steam and hot water plants also are in operation but, to date, no power plants have been developed using either the dry hot rock or the geopressured systems.

The location of geothermal sources is controlled by geologic events primarily of the late Cenocoic period and tend to follow lines of tectonic activity. Other than location, the primary technical factors dictating utilization of geothermal sources are:

- Temperature of the reservoir
- Flow rates available from the wells
- Depth of the reservoir
- Purity of the geothermal fluids.

TABLE 2. Geothermal Power Plants of the World

Geothermal Power Plant (1975)	1975 Capacity, MWe	Number of Turbines	Reservoir Type*	Res. Temp. °C	Res. Area, sq. mi.	No. Producing Wells	Ave. Well Depth (ft)	Production Bore Diam. (in.)	Comments	
The Geysers, USA	520	11	DS	250	180	88	3000	$8\frac{5}{8}$	Growth:	1400 MWe by 1985. Generation began in 1960 at 12.5 MWe.
									Geology:	Metamorphosed highly fractured Franciscan shale and sandstone.
									Disposal:	Steam is condensed and reinjected. Noncondensable gases, primarily CO_2 and H_2S, are vented to atmosphere
Larderello, Italy Monte Amiata, Italy	420	15	DS	200	150	467	3300	$13\frac{3}{8}$	Growth:	Generation began in 1904.
									Geology:	Cavernous limestone and anhydrite with impermeable schistous clays above.
									Disposal:	Condensate gases to natural drainage. High in boron.
Wairakei, New Zealand Kawerau, New Zealand Broadlands, New Zealand	193	7	FS	270	900	61	2500	$7\frac{5}{8}$	Growth:	300 MWe projected. Production began in 1958.
									Geology:	Rhyolitic pumice breccia and open jointed welded tuft, in region of volcanism and faulting. Pleistocene.
									Disposal:	Brine is discharged into a large river. Land subsidence is occurring.
Hachimantai, Japan	10	1	?	?	?	?	3000	?	Growth:	Production started in 1971. Data lacking.
Hatchobaru, Japan	50	2	FS	?	?	?	?	?	Growth:	Under construction, data lacking.
Matsukawa, Japan	20	1	DS	240	*	5	3600	$7\frac{5}{8}$	Growth:	60 MWe expected by 1980. Production started in 1966.
									Geology:	Andesitic volcanics. Pleistocene.
									Disposal:	Condensate discharged into natural drainage.
Onikobe, Japan	25	1	DS	280	?	12	3000	?	Growth:	Construction started April 1973. Completion due 1975.
Onuma, Japan	10	1	FS	260	?	3	4500	?	Growth:	Operation began in 1973 at 4.8 MWe.
Otake, Japan	13	1	FS	200	?	5	3000	$7\frac{5}{8}$	Growth:	Operation began in 1967 at 12 MWe. 60 expected by 1980
Cerro Prieto, Mexico	75	2	FS	300	10	15	4500	$7\frac{5}{8}$	Growth:	150 MWe by 1982.
									Geology:	Highly fractured sandstone and shale at The San Jacinto Fault Zone. Late Tertiary.
									Disposal:	Brine follows natural drainage to Gulf of California. Condensed steam supplies potable water.
Pathe, Mexico	3.5	1	FS	150	?	12	1000	?	Growth:	Experimental plant started in 1958. No expansion planned.
Namufjall, Iceland	3.0	1	FS	260	20	4	2200	?	Growth:	3 MWe plant in operation since 1969. 60 MWe construction started in 1974.
Krafla, Iceland	60								Geology:	Late Quaternary centers of dacitic and rhyolitic volcanism.
Paratunka, USSR	0.75	1	HW	82	?	8	1300	$7\frac{5}{8}$	Growth:	Binary cycle operation with Freon began in 1964.
Pauzhetka, USSR	5.0	2	FS	170	?	8	1000	?	Growth:	Operation began in 1967 at 3 MWe. Expansion to 20 MWe is planned.
Makhachkala, USSR	12	?	FS	160	?		12,000	?	Growth:	Under construction.

*Reservoir type: DS = dry steam, FS = flashed steam, HW = hot water (not flashed)

Use of a given resource is determined primarily by how these factors affect the economics of power generation. As was shown in Figure 1, reservoir temperatures of approximately 100°C are required for binary cycle systems while temperatures in excess of 150°C are generally required for flash steam or dry steam utilization. Of the power plants listed in Table 2, only the binary cycle plant at Parantunka, USSR, uses reservoir temperatures less than 150°C. However, with the current research and development of binary cycle systems, this picture is expected to change in the near future.

The effects of temperature and flow rate on electric power production are shown in Figure 2 for the dry steam (vapor dominated) and flashed steam systems (White and Williams, 1975). Typical wells in use today produce between 2 and 10 MW (electrical equivalent) per well at flow rates varying from 3 to 300 kg/sec. As noted in Figure 2, greater flow rates are required from the flashed steam systems since only 20 to 25% of the hot water flashes to usable steam and the rest must be reinjected or dumped.

From Figure 3, the effect of the depth of the reservoir (or more accurately the cost of the well) on the cost of power production can be seen. The three diagrams show constant cost curves as a function of flow rates and temperatures for three different well costs: $150,000, $300,000 and $500,000. Assuming the higher cost wells are the deeper wells, the effects of depth on power production can be seen by setting a fixed well temperature and flow rate for all three cases. For example, at a flow rate of 400,000 lb/hr (or 225 kg/sec) and a temperature of 200°C, the power production cost is 21, 25, and 30 mills/kWh for well costs of $150,000, $300,000 and $500,000, respectively.

Drilling costs increase exponentially with depth and, consequently, geothermal wells greater than 15,000 ft are not yet economically competitive, even though the technology exists to drill deeper wells. The cost data of Figure 3 do not include the number of dry holes that may be drilled to bring in a reservoir, nor does it consider fluid chemistry, well spacing, or replacement rate. Fluid composition, particularly the high acidic brines, may have a very large impact on power costs.

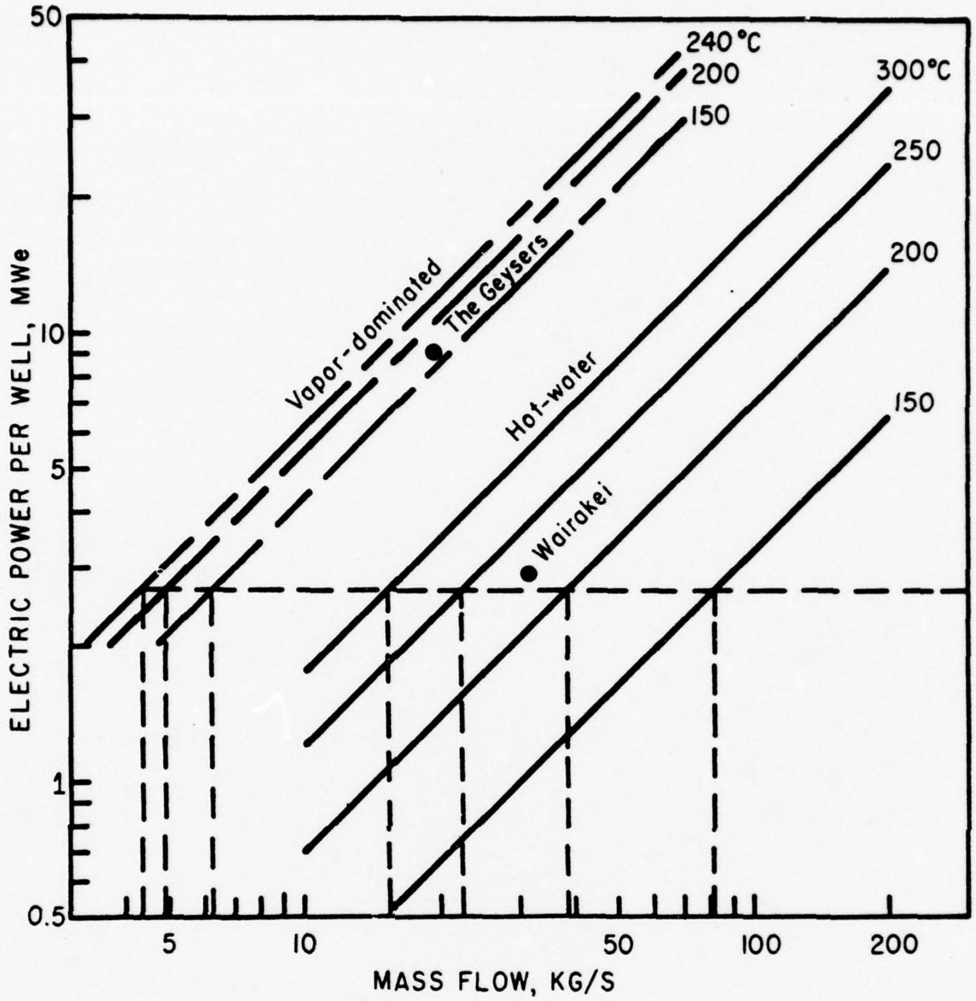
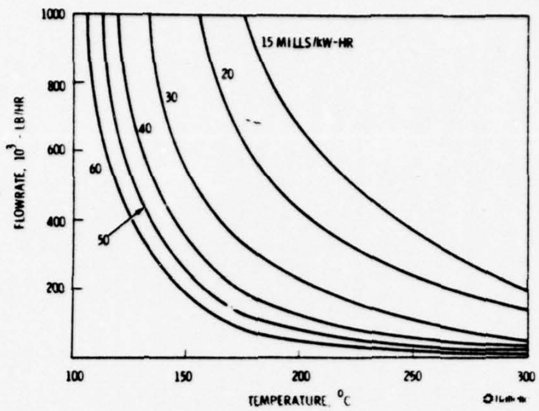
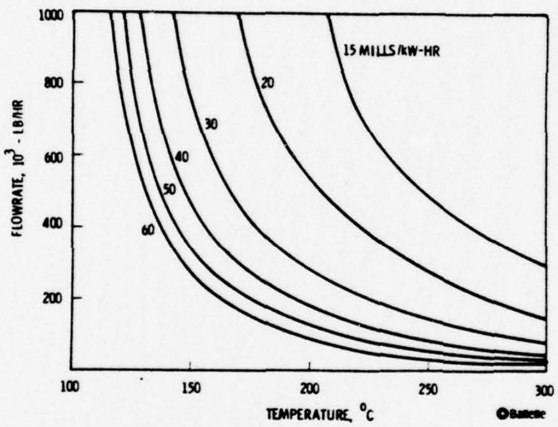


FIGURE 2. Electric Power Per Well as a Function of Mass Flow for Various Temperatures of Hot-Water and Vapor-Dominated Systems

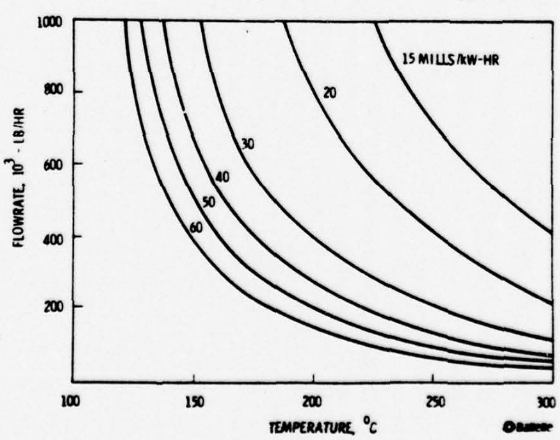
Source: White and Williams, 1975



Isocosts for Hydrothermal Resources at a Well Cost of $150,000



Isocosts for Hydrothermal Resources at a Well Cost of $300,000



Isocosts for Hydrothermal Resources at a Well Cost of $500,000

FIGURE 3. Power Production Costs as a Function of Temperature, Flow Rate, and Well Cost

Source: Bloomster and Engle, 1976

The binary cycle systems using Freon or isobutane as a secondary fluid probably will not produce cheaper power than dry steam or flash steam systems. The primary advantage of a binary cycle system is that it can use lower temperature reservoirs, i.e., a more common resource, than other geothermal systems. However, because of the low enthalpy fluids, low temperature wells will need to produce large flow rates to obtain significant power for binary cycle power plants. Although Russia has operated a binary cycle plant at Parantunka since 1964, the western world has had no operating experience with such a plant and only theoretical economic comparisons are available. However, research is being sponsored by ERDA to gain actual operating experience.

The Coso Hot Springs has been identified as a prime candidate for development of geothermal energy at the military installation (Austin and Pringle, 1974; Combs, 1973, 1975, 1976). The Coso geothermal area, located primarily on the China Lake Naval Weapons Center, in Inyo County, California, (Figure 4) is situated in a tectonically active area of young basaltic and rhyolitic volcanism (Duffield, 1975). Hot springs, fumaroles and other surface phenomena associated with the young volcanism have caused the USGS to classify the area as a Known Geothermal Research Area (KGRA). In the fall of 1974 intensive study was begun including 1) geologic mapping, 2) geochemistry of the late Cenozoic rocks, 3) geochronology of the late Cenozoic volcanic rocks, 4) geochemistry of the geothermal fluids, 5) further study of gravity, 6) aeromagnetics, 7) additional heat flow determinations, 8) both active and passive seismic investigations, 9) patterns of arrival times for teleseisms, 10) first order levelling studies, 11) geodimeter trilateration and 12) additional geoelectric and electromagnetic surveys. These investigations involve personnel of the USGS, BNW, China Lake Naval Weapons Center (NWC) and the University of Texas at Dallas (UTD).

The current Coso Geothermal Project under ERDA funding started in December 1975 at $675K for BNW in FY76. The NWC also received $75K in direct funding from ERDA, Division of Geothermal Energy, for their project activities in FY76. Transition quarter funding was $500K for BNW and $50K

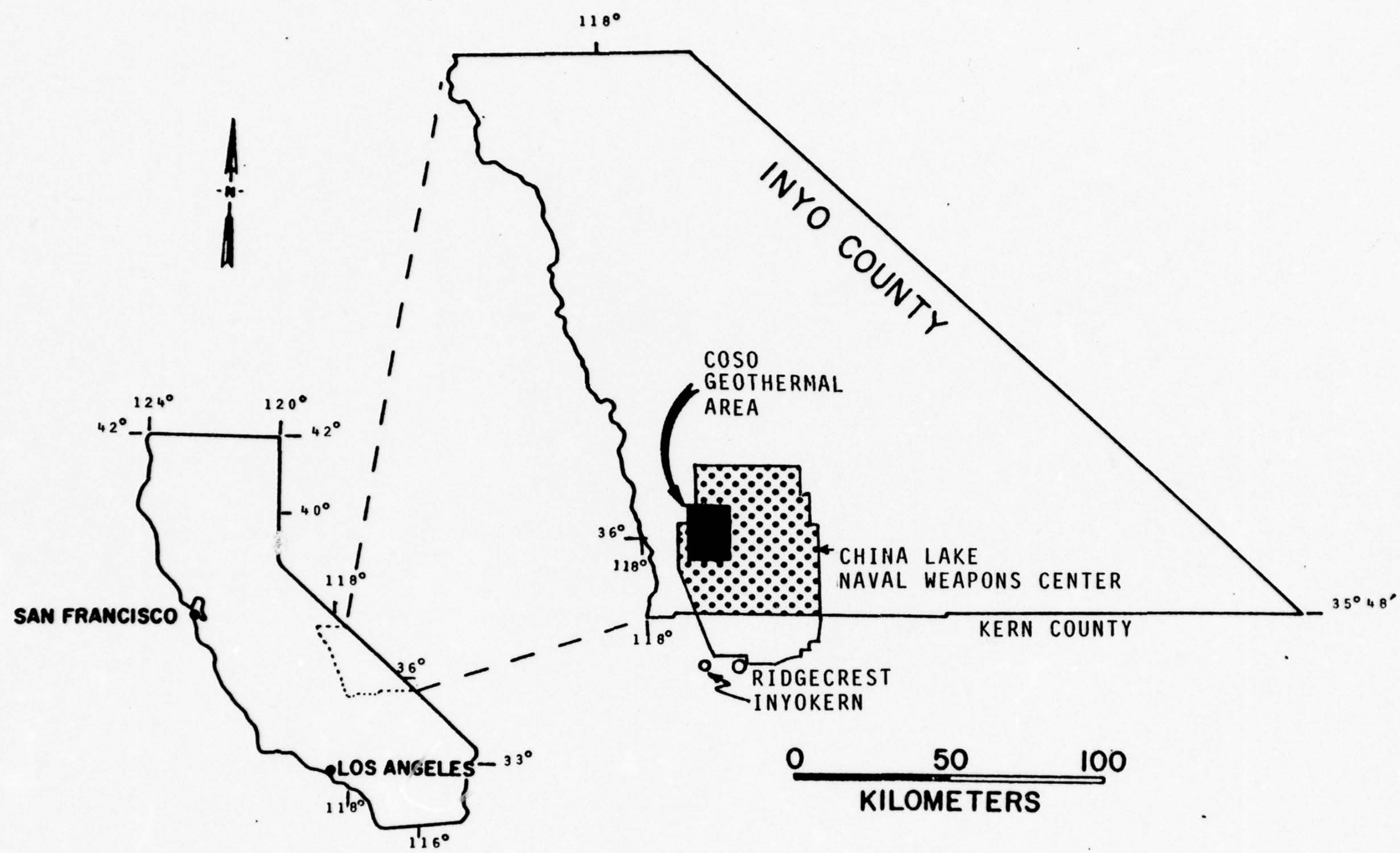


FIGURE 4. Coso Geothermal Area, California. (Shaded rectangle depicts area of the microearthquake investigation.)
Source: Combs, 1976

for NWC, and FY77 budget is $1,300K for BNW and $150K for NWC. Under this project an additional 18 heat flow holes (100 m deep) have been drilled, heat flows evaluated, microseismic measurements made, and drilling of the first deep hole (1200 m) has begun. During FY77 two deep slim holes are expected to be drilled, followed by two to four additional deep holes the following year.

The objectives of the Coso Geothermal Project are to: 1) investigate the potential geothermal resource of the Coso KGRA as part of the national resource assessment program for dry hot rock and 2) assess the effectiveness of the slim holes drilling (less than 15 cm diameter and up to 1500 m depth) as an exploratory tool for geothermal energy.

Results show that heat flows vary from 2.0 to 16.0 heat flow units (μ cal/cm^2 sec) with measured temperatures of 100°C at 200 m at the site of the first deep slim hole. During the summer of 1974, and again in 1975, seismographs installed in the KGRA showed considerable microearthquake activity. Activity varied from only a few events per day to more than 115 events per day. During 33 days of recording more than 2000 events of S-P seismic wave times of less than 3 seconds were detected. Strain release in the KGRA occurs primarily in swarm-type sequences, whereas earthquakes outside the area occur as main after-shock sequences. The S-P wave velocities infer a Poisson's ratio of 0.16 compared with values of 0.25 to 0.30, which are normally observed. The low value for Poisson's ratio probably indicates that the shallow surface is either deficient in liquid water or that these void spaces (cracks) are filled with steam. Electrical resistivity measurements of the area show conductive zones near the fumaroles. A summary of these geophysical surveys is shown in Figure 5. Although the area has a very complex geology it appears to have a potential for the production of hot brines in the shallow zones, for the production of dry steams from certain areas, and for areas where hot dry rock may be located.

2.3 GEOPRESSURED SYSTEMS

Geopressured systems are sedimentary zones in Tertiary basins in which abnormally high fluid pressures and temperature are found. These zones are

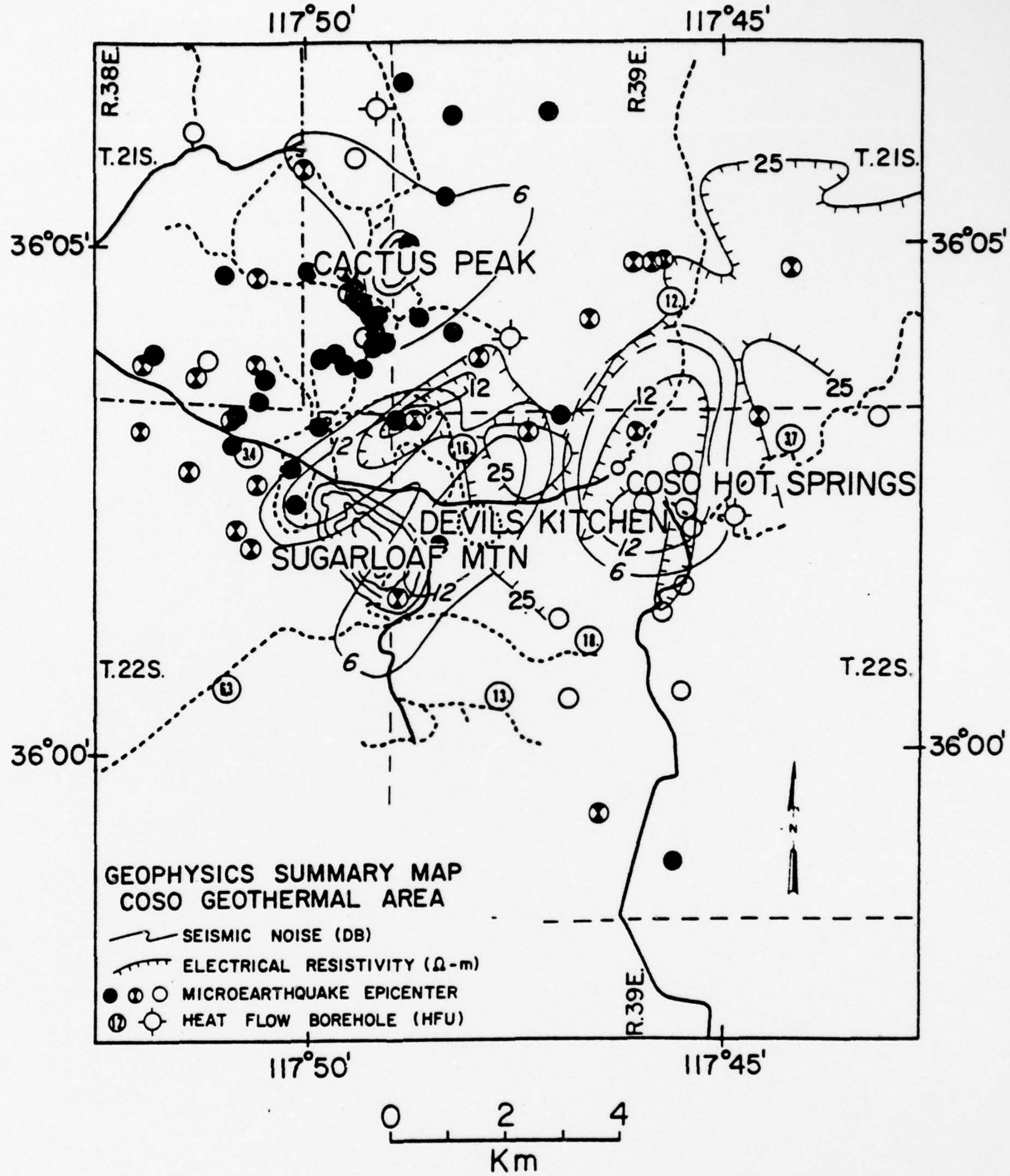


FIGURE 5. Geophysics Summary Map of the Coso Geothermal Area
Source: Combs, 1976

found world wide, typically at 6,000 to 12,000 ft levels in which the hydrostatic pressures exceed the hydrostatic head and, in fact, approach 75 to 90% of the lithostatic head (Herrin, 1973). The over pressure zones occur in layers from a few feet thick to several thousand feet thick, zones in which the overburden rides on undercompacted clastic sediments (sand and clay or shale). Typically these zones have a porosity 6 to 8% greater than would occur at that depth if full compaction took place. Consequently, permeabilities of these zones tend to be high, up to 25 millidarcies, with water viscosities on the order of 0.2 to 0.3 centipoise. The water is usually a chloride bicarbonate, slightly alkaline (pH 7.5 to 8.5).

From an energy standpoint, an interesting feature of these pressured systems is that the water contains large volumes of hydrocarbon gases, in particular methane, which is soluble in water. Often 10 to 15 standard ft^3 of methane/barrel of fluid, or approximately 0.5 ft^3/gal of water, can be extracted from the water as part of the energy producing system. Fluid temperatures vary from 150 to 200°C and, consequently, the fluids can be used for power production or space heating, etc. Actually, energy can be extracted from three sources in geopressured systems: 1) the thermal energy from the high temperature fluids, 2) the thermal energy from the methane, and 3) the mechanical energy available from the artesian flow.

The artesian systems are bound and compartmentalized by regional faults and may cover thousands of square miles. Compartments tend to be linked together in sedimented belts by the faults with the belts extending hundreds of miles. Although these systems occur in many places, the best explored is in the northern Gulf of Mexico basin along a fault system about 750 miles long on the Texas and Louisiana Gulf coast. Since the 1920s, more than 300,000 wells have been drilled in search of petroleum and have penetrated geopressured zones in this basin. Herrin (1973) lists the known occurrence of geopressured systems as follows: the U.S. (Arkansas and California, Louisiana, Oklahoma, Texas, Wyoming), the Arctic Islands, Mexico, South America (Venezuela, Trinidad, Columbia, Argentina), Japan, New Guinnea,

Indonesia, South China Sea, Burma, India, Iraq and Pakistan, Algeria, Morocco, Nigeria, Mozambique, Austria, France, Germany, Holland, Italy, Hungary, Poland, Rumania and Russia. Department of Defense installations exist over geopressured regions in the United States, Holland, West Germany, Berlin, Italy, South China Sea, Alaska, Canada, Taiwan and Japan. Energy could be extracted from these reservoirs for DOD use but to date no such applications exist and additional R&D projects are needed. A good place to extract this energy is in the Gulf coast region of the United States because of the knowledge available from oil exploration activities.

Scientists from the U.S. Geological Survey (Papadopulos, et al., 1975), in their assessment of geothermal resources within the United States, have divided the Gulf coast region into 21 sub-sections as shown in Figure 6. The belted zones tend to follow sedimentary sequences in Mesozoic time corresponding to the dumping of large volumes of sand and clay along the Gulf of Mexico by the great river systems of the mid-continent. Consequently the belts generally coincide with subsurface distribution of different sediments from different periods of time. As Papadopulas, et al., have them labelled:

The A belt from the Eocene-Wilcox sediments
The B belt from the Jackson-Yugea beds
The C belt from the Frio-Vicksburg beds
The D belt from the Frio
The E belt from the Frio-Anahuec
The F belt from the Fiocene

As a result of extensive studies of thousands of existing wells, Table 3 was developed as an estimate of the energy stored in the 21 zones. The total energy stored is estimated to be 7.125×10^{22} joules (1.979×10^{16} kWh). For a comparison, the total electric energy generation for the United States in 1974 was 1.865×10^{12} kWh. At that rate, the stored energy in the Gulf coast basin represents more than ten thousand years of supply for the United States. Although only a portion of this stored energy can actually be utilized, by any estimation it represents a large source.

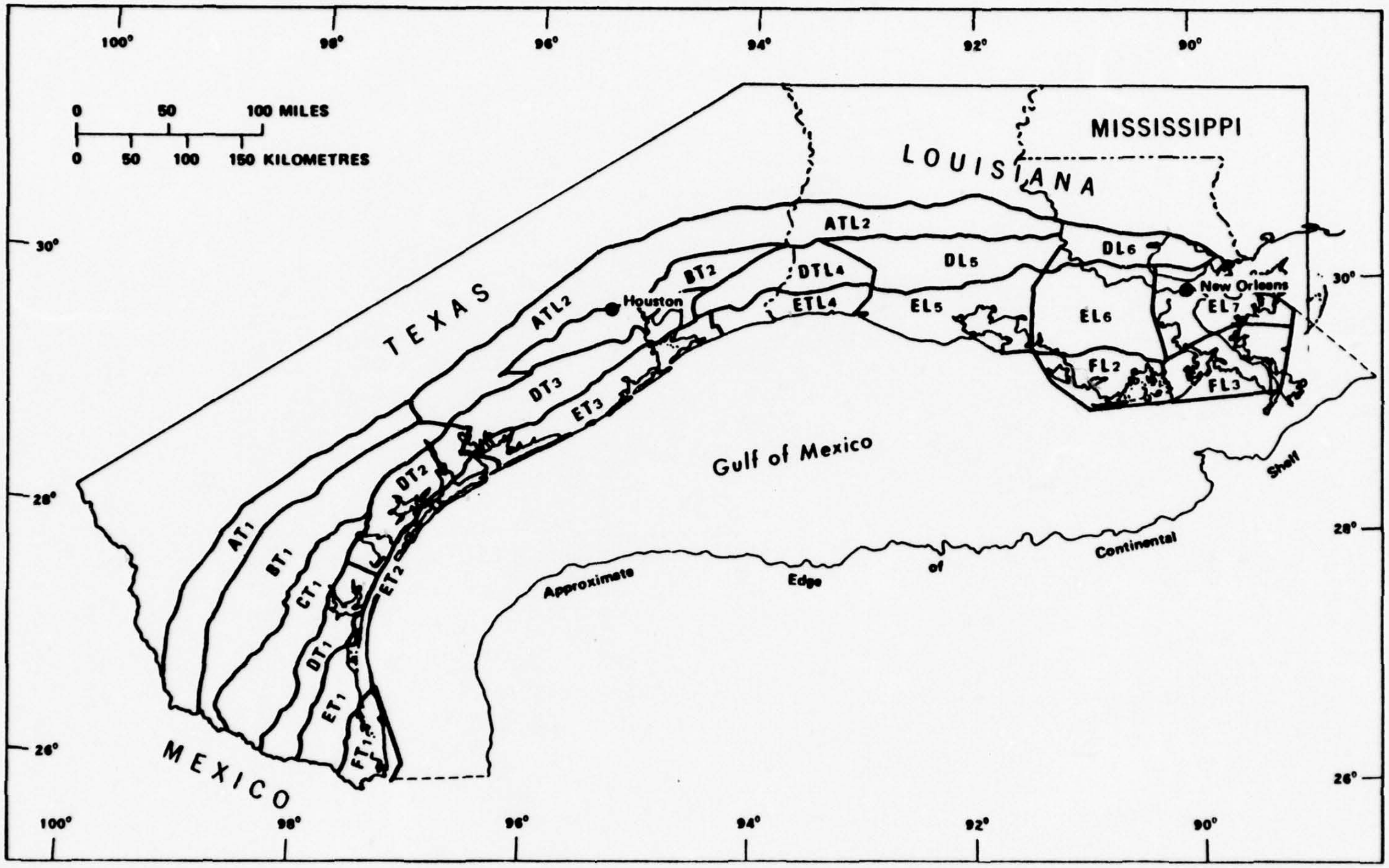


FIGURE 6. Assessed Geopressured Zones and Their Division into Subareas (AT_1, BT_1, and so on)
Source: [1]Papadopulos, et a., 1975

TABLE 3. Assessment of "Recoverable Energy" Under the Assumed Basic Development Plan, Plan 1

Source: Papadopulos, et al., 1975

Reservoir	Available formation drawdown	Flow rate-drawdown ratio	Well spacing	Number of wells	Volume of water produced	Thermal energy	Methane Energy: Volume	Methane Energy: Thermal equivalent	Mechanical energy
	m	10^{-5} m^2/s	km		10^{10} m^3	10^{18} J	10^{10} std. m^3	10^{18} J	10^{18} J
AT_1	3,060	4.9	3.1	930	8.80	58.5	96.7	36.5	2.1
ATL_2	2,410	6.2	3.1	2,180	20.64	117.1	173.3	65.4	4.5
BT_1	2,370	6.3	3.9	890	8.43	52.2	80.1	30.2	1.8
BT_2	2,690	5.6	3.5	450	4.20	23.6	32.0	12.1	1.0
CT_1	2,780	5.4	2.6	1,210	11.46	71.5	102.0	38.5	2.6
DT_1	3,250	4.6	2.4	840	7.95	49.6	72.4	27.3	1.9
DT_2	3,090	4.9	3.2	500	4.73	29.3	43.6	16.5	1.1
DT_3	2,580	5.8	3.5	600	5.68	31.9	45.5	17.2	1.3
DTL_4	2,620	5.7	3.7	370	3.50	18.4	25.6	9.7	0.8
DL_5	3,730	4.0	2.9	830	7.86	48.4	62.9	23.7	2.1
DL_6	3,950	3.8	2.5	590	5.59	33.3	46.4	17.5	1.5
ET_1	2,640	5.7	2.4	930	8.80	54.2	77.5	29.2	2.0
ET_2	2,900	5.2	3.2	190	1.80	10.8	16.9	6.4	0.4
ET_3	2,550	5.9	3.2	730	6.91	37.0	53.9	20.4	1.5
ETL_4	2.950	5.1	3.5	280	2.65	13.9	17.8	6.7	0.6
EL_5	3,730	4.0	2.7	1,110	10.51	66.2	84.1	31.7	2.8
EL_6	3,730	4.0	2.6	1,310	12.40	75.1	95.5	36.0	3.3
EL_7	3.680	4.1	2.3	1,180	11.17	59.8	95.0	35.8	2.9
FT_1	2,920	5.1	2.7	310	2.93	18.1	29.9	11.3	0.7
FL_2	3,430	4.4	2.5	750	7.10	40.1	51.8	19.6	1.8
FL_3	4,180	3.6	2.5	980	9.28	52.0	76.1	28.7	2.6
Totals				17,160	162.33	961.0	1,379.2	520.4	39.3

The stored energy comes from three sources: thermal energy, methane, and mechanical energy. To calculate the stored thermal energy, Papadopulos, et al. calculated the heat content of the water above 15°C using an average specific heat of 4,100 J/kg/°C. Thermal energy of the methane was calculated assuming a heat equivalent of 3.77×10^7 J/m^3 based upon the measured and estimated methane content of the geothermal fluids. Mechanical energy was calculated based upon the hydraulic head that would be available at the surface of the land for conversion of the potential energy to electric energy. Of the three sources, thermal energy of the water represents 64%, methane 35%, and mechanical energy about 1% of total stored energy.

Herrin (1973) has proposed two sites in southern Texas where testing of the geopressured reservoir concept can take place. The two sites proposed are located south of Corpus Christi, Texas, near the Mexican border, as shown in Figure 7. These sites have been proposed after consideration of both technical and environmental features and in both cases the existence of geopressure systems has been verified by existing wells. The characteristics of the Sebastian site are summarized in Table 4 and the Port Mansfield site in Table 5. The Sebastian site is in a remote agricultural section where cotton is grown and is adjacent to scrub woodlands and a wildlife refuge. Waste waters can be disposed of by an existing drainage system and land subsidence would have a minimal effect because of the remoteness from towns and villages. The Port Mansfield site is approximately 7 miles inland from the Laguna Madre of the Gulf of Mexico, on land belonging to the King Ranch, and about 3 miles northwest of the Willimar oil fields. It is located about 4 miles east of the small ranch community of El Sauz. The region is almost completely useless for crop growing because of the high salinity and frequent water logging of the soil, but it is being used for cattle range land. The particular site selected has been leased by the Federal government for a U.S. Naval Research station for satellite detection. Again, the effect of subsidence and other project activities on the environment would be minimal.

Based upon the information available at the two sites, Herrin recommends construction and operation of a pilot plant for electric power production,

FIGURE 7. Texas Gulf Coast
Source: Herrin, 1973

TABLE 4. Sebastian Site
Source: Herrin, 1973)

Depth to geopressured aquifers	14,300 ft
Thickness of aquifer series	700 ft
Corrected temperature (°F)	320-325
Pressure (psi)	11,600
Salinity (ppm)	2000-6000
Areal extent of faulted block containing aquifers	10 x 30 miles
Existence of evidence that low-salinity geopressured conditions exist elsewhere in block	Yes (H555)
Porosity of aquifers	20%
Permeability of aquifers	100-135 millidarcys

TABLE 5. Port Mansfield Site
Source: Herrin, 1973

Approx. depth to geopressured aquifers	12,650-15,660 ft
Thickness of aquifer series	800 ft
Corrected temperature (°F)	267-329
Pressure	10,000-14,381
Salinity	20,000
Areal extent of faulted block containing aquifers	About same as San Sebastian
Existence of evidence that low-salinity geopressured conditions exist elsewhere in block	Yes (C-177)
Porosity of aquifers	20%
Permeability of aquifers	100-135 millidarcys

using water from a single well, preferably at the Sebastian site. The principal objectives of the five-year pilot project would be as follows:

1. Demonstrate the feasibility of power production from thermal and mechanical energy storage in a geopressured subsurface reservoir.
2. Determine the production pressure history of the well. Evaluate the contributions to production from gas drive and de-watering of the shale.
3. Study the change in water chemistry with production as an indication of the change in shale composition in the reservoir.
4. Develop optimum methods for converting the mechanical energy stored in the over pressured water to electrical energy.
5. Investigate the use of the facility as a standby power facility. Determine the effect of shutting down the well for long periods of time.
6. Determine, by use of sensitive instrumentation, the surface effects resulting from withdrawal and reinjection of large amounts of water required for power production.

The accomplishment of these objectives would require drilling of one to three deep wells, a similar number of shallower wells into normal pressured formations for reinjection, installation of a 5 to 10 MW turbine alternator system, installation of surface plumbing and well control equipment, preparations and arrangements for disposal of saline waste water, completion of legal arrangements for land use from the current owners, preparation of an environmental impact statement, and installation and monitoring of instrumentation to gather the required scientific information. Successful penetration of the geopressure reservoir is essentially assured because of data available from other wells in the region. The estimated characteristics of a typical deep well are given in Table 6. Under the given assumptions, each well could reasonably be expected to produce about 2.5 MW of electrical power with an estimated lifetime of 20 to 30 years.

TABLE 6. Estimated Production Well Characteristics at the Sebastian Site.

Source: Herrin, 1973

Water Viscosity		0.2 cp
Total Salinity		2000-6000 ppm
Sand Porosity		0.25
Sand Permeability	good	0.3 darcy
	average	0.05 darcy
Reservoir Pressure		12,000 psi
Well Head Pressure		5000 psi
Well Depth		14,600 ft
Bore Hole Radius		0.3 ft
Well Production		50,000 bbls/day (2.1×10^6 gal/day)
Well Head Temperature		325°F
Plant Discharge Temperature		212°F
Thermal Energy (ΔT = 113°F)		942 Btu/gal
Thermal Conversion Efficiency		10%
Power Production		2.5 MWe/well*

*Thermal equivalent of recovered methane and of the mechanical energy are not included. With these factors included the energy would be about 4 MW/well.

2.4 MAJOR FACTORS AFFECTING GROWTH

The primary factors affecting growth of the geothermal industry at this time are:

- Need for less expensive drilling
- Need for control of corrosion, erosion, precipitation and scaling
- Better geophysical and geochemical exploration techniques
- Development of certain high temperature equipment, such a downhole pumps

• A simplification of legal and environmental constraints

Of these, only the first two topics were addressed in this study.

Drilling Technology

One of the most expensive investments for any geothermal development is the drilling of production wells. It is not unusual for a well to cost $1 million, which, when completed, will produce about 5 MW electrical, yielding a capital investment ratio of $200/kW. That cost includes drilling, casing, cementing, well completion and wellhead equipment. It does not include any of the above ground plumbing and plant costs. The cost of nonproducing wells and reinjection wells can cause drilling costs to become one of the largest single factors of geothermal development. From a national standpoint, drilling operations will cost about $4 billion in 1976, most of which is spent on drilling for oil and gas. This represents about 2% of the $200 billion spent annually by the entire U.S. energy industry. However, a large portion of this industry directly depends upon the success of the drilling operation for the development of new resources.

Historical developments of the drilling industry fall into two categories. Deep large diameter production wells are drilled with a conventional rotary drilling rig developed by the oil industry. The diamond drill rig, on the other hand, was developed by the hard rock mining industry to produce continuous core samples and not to be used in production. It appears both technologies will merge in the development of geothermal resources.

The diamond drilling, or so-called slim hole drilling, is typically done with a small drill rig mounted on the back of a truck for mobility, and is usually limited to holes less than 6 in. in diameter and 5000 ft deep. Such holes are drilled primarily to obtain information and not for the production of energy. The primary use for the slim hole drilling in geothermal energy development will be during exploration to locate and evaluate our resources.

Since slim hole drilling uses a diamond coring bit, a continuous lithological record is obtained as the drilling is done. The core is cut and

held in a core barrel, which is attached to a wire line for rapid removal without pulling the drill string. The cores can be used for evaluation of minerological, chemical, and physical properties. Such operations enable mining engineers and geologists to delineate the boundaries of ore bodies and probably can be used equally effectively on geothermal reservoirs. The diamond drill bits typically run at fairly high speeds (200 to 1200 rpm) and cost in the order of $100 to $500/bit. Under difficult drilling operations the bits may last for only about 100 ft before they are extracted and salvaged for any remaining diamonds.

The drill rig is operated with a two man crew and is limited by its lifting capacity and the holding capability of its braking system. The mud mixing system for the slim hole drilling rig is fairly simple, using 2 to 3 portable tanks 6 to 10 ft in diameter and perhaps 2 ft deep. Because slim hole drilling is done with fairly small and simple drill rigs, requiring little auxiliary equipment, environmental impacts of exploratory drilling and, consequently, exploratory costs are low.

The primary disadvantages of slim hole drilling derives from the small diameter of the hole. The probability of leaving a hole due to bridging or caving is greater, and fishing for lost or damaged equipment is more difficult than in larger diameter holes. Furthermore, when the hole is completed it cannot be used as a production well because it restricts flow volume. Instrumentation and blowout prevention systems are much more limited than for the rotary drilling rig. Consequently, slim hole drilling will find its place in the geothermal industry as an exploration tool to be used with other geophysical surveys and not as a replacement for rotary drilling. Costs for the slim hole drilling, as of 1976, range approximately from $30 to $50/ft, including casing, cementing and wellhead equipment.

Rotary drill rigs vary in size from those not much bigger than slim hole drill rigs to the massive systems for deep ocean drilling. Hard formations are drilled with tri-cone carbide insert bits which cost $1000 to $3000 and typically run from 100 to 400 ft. They are usually rotated at less than

100 rpm and the axes of the cones are offset so that a skidding-rolling action crushes the rocks.

The drill string consists of steel tubing which is rotated by a kelly, a special piece of rectangular steel tubing, attached at the top. As the kelly slides through a close fitting rotary table on the floor of the drill rig, the kelly is driven or rotated, thereby causing the entire drill string to rotate. As with slim hole drilling, drilling fluids are pumped down the center of the drill string, and around the drill bit to cool it and remove drill cuttings. Sometimes air or water, or a combination thereof, is used in place of the water-mud mixtures.

The rotary table is driven through an appropriate transmission system by 3 to 5 large diesel engines, often with a total of 3000 or more horsepower. The drill rig is operated by a crew of five or more men per shift to keep the drill rig operating on a 24-hr basis. The deepest holes currently being drilled are 30,000 to 35,000 ft with new depth records being set every year. However, the average depth is about 5500 ft for the 20,000 to 50,000 wells completed each year by the U.S. drilling industry.

Most of these holes are drilled in relatively soft sedimentary formations in search of gas and oil. The drilling costs per foot under these conditions are \$30 to \$50/ft, a deceptively low cost for typical geothermal drilling. Most geothermal wells are drilled in very hard igneous formations at drilling costs 2 to 3 times the above figures.

The rotary drilling industry has had many years to mature into a highly specialized well-developed technology, largely without the support of government research. Each operation (drilling, mud preparation, logging, casing, cementing, well testing and completion) is done by companies who often specialize in only one of the operations. From a cost standpoint, this has proven highly efficient since most of the specialists are needed for only a short period of time during the total drilling operation.

As the wells are drilled to greater and greater depths, the costs per foot increase exponentially because proportionally more and more time is

devoted to nonproductive drilling operations. These are primarily associated with so-called round trip costs. A drill string is typically assembled in 30 ft sections of coupled pipe. As the drill bit is later extracted from the hole, these sections of drill pipe are uncoupled and stacked. Consequently, time is lost each time a bit is changed, a core is taken, or logging is performed. For these reasons, the current technology will probably reach its economic depth limit prior to 50,000 ft.

High temperatures cause the second basic limitation with the current technology. At temperatures above 250 to 300°C, the journal bearings on the drill bits do not function properly, the carbide inserts fall out (due to different coefficients of expansion), logging and downhole instrumentation systems often fail to work, the drilling fluids break down and don't maintain the required cooling and cleaning characteristics, and cements do not harden properly. Furthermore, the combination of high temperatures and depths beyond 35,000 ft will prove particularly devastating as the tensile strength and compression strength of drill strings and casings are stretched beyond their limits (Patterson, Sabels, and Kooharian, 1973).

Novel drilling techniques are currently under investigation in various places around the world. One of the best textbooks on this topic was prepared by Maurer (1968) in which he lists some 25 drilling techniques and gives maximum estimated drilling rates. Table 7 has been taken from Maurer's text to illustrate the diversity of possible drilling techniques. Electric heating and laser techniques have been under investigation at Los Alamos Scientific Laboratory for several years, although these techniques are still confined to laboratory use.

One of the most promising new techniques is under development by M. I. Tsiferov, a Russian explosives expert, who, since 1948, has been working on an underground rocket (Stevovich, 1975). The rocket is now relatively well developed and is registered under a Soviet patent, No. 79119. It is approximately 20 cm in diameter and 2 m long. It drills by releasing a stream of high pressure gas (at pressures between 500 and 2500 atm) to

TABLE 7. Estimates of Maximum Drilling Rates for 20 cm Diameter Novel Drills in Medium-Strength Rock.

Source: Maurer, 1968

Drill	Status	Rock Removal Mechanism	Specific energy (joules/cm^3)	Maximum power to rock (h.p.)	Maximum potential drilling rate (cm/min)
Rotary[a]	Field drill	Mechanical	33–300	20–30	14–85
Spark[a]	Laboratory drill	Mechanical	200–400	100–200	35–140
Erosion[a]	Laboratory drill	Mechanical	2000–4000	1000–2000	35–140
Explosive[a]	Field drill	Mechanical	200–400	75–100	26–70
Forced-flame	Field drill	Spalling[b]	1500	300–600	28–56
Jet-piercing	Field drill	Spalling[b]	1500	100–200	9–18
Electric disintegration	Laboratory drill	Spalling[c]	1500	100–150	9–14
Pellet[a]	Laboratory drill	Mechanical[a]	200–400	10–20	4–14
Turbine[a]	Field drill	Mechanical[a]	400–1300	30–40	3–14
Plasma	Laboratory tests	Spalling[b]	1500	80–120	8–11
Electric arc	Laboratory tests	Spalling[b]	1500	45–90	4–8
High-frequency	Shatters rocks	Spalling[b]	1500	30–60	3–6
Plasma	Laboratory tests	Fusion	5000	80–120	2–3
Electric heater	Laboratory drill	Fusion	5000	50–100	1–3
Electric arc	Laboratory tests	Fusion	5000	45–90	1–3
Nuclear	Conceptual	Fusion	5000	1250–2500[e]	1–3
Laser	Small holes	Spalling	1500	12–24	1–2
Electron beam	Small holes	Spalling[b]	1500	10–20	1–2
Microwave	Shatters rock	Spalling[b]	1500	10–20	1–2
Induction	Shatters rock	Spalling[d]	1500	5–10	0.5–1.0
Laser	Small holes	Fusion	5000	10–20	0.3–0.6
Electron beam	Small holes	Fusion	5000	10–20	0.3–0.6
Electron beam	Small holes	Vaporization	12,000	10–20	0.1–0.2
Laser	Small holes	Vaporization	12,000	7–14	0.1–0.2
Ultrasonic[a]	Laboratory drill	Mechanical	20,000	5–10	0.04–0.07

[a] Water-filled borehole.
[b] Limited to highly spallable rock such as taconite.
[c] Limited to highly spallable rock with high electrical conductivity.
[d] Limited to highly spallable rock with high magnetic susceptibility.
[e] 100 cm diameter drill.

disintegrate the rock immediately in front of the rocket head. Simultaneously, side jets of gas cause the rocket to rotate while a flame vortex rocket engine in the rear drives the rocket forward and ejects disintegrated material. The rocket is reported to have obtained penetration rates of 1 m/sec while opening a hole of about 1 m in diameter at the surface. The rocket has equivalent energy of 10,000 to 50,000 hp and has been field tested on the drilling of water wells for irrigation purposes. For these shallow wells it drills a 1 m diameter hole, approximately 17 m deep, in about 18 sec and can be recovered and refueled for repeated operation. It can carry 200 kg of fuel and can be refueled in 20 min. Potentially, a sequence of these rockets could be used to drill a single hole to great depths. A second variation of the same rocket uses a sequence of explosions at the rocket head in lieu of the continuous gas jet. At present, no data are available regarding the material for construction of the rocket, type of explosives (liquid, solid or atomic) nor the method of retrieval or control. However, the rocket has been the main topic of discussion at meetings of the USSR Academy of Sciences and is considered to be the best prospective tool for drilling.

Chemistry of Geothermal Fluids

The four principal problems associated with chemistry of geothermal fluids are corrosion, erosion, precipitation and scaling (CEPS). All four of these problems can occur at various places in a power plant or more generally in any system that utilizes geothermal fluids.

Many geothermal fluids tend to be very corrosive because of a low pH (1.5 to 2). Corrosion may occur in a variety of forms, each of which requires a special study by a chemical engineer: uniform corrosion, galvanic corrosion, pitting and crevice corrosion, fretting and erosion corrosion, intergranular corrosion, corrosion fatigue, sulphide corrosion and hydrogen embrittlement, stress corrosion cracking, and high temperature oxidation.

Extensive corrosion studies are underway at a number of research laboratories. One of the largest projects is under the direction of

D. W. Shannon at Battelle, Pacific Northwest Laboratories and sponsored by ERDA (Shannon, 1975). A parallel project also directed by Shannon is sponsored by Electric Power Research Institute.

Simplified analytical and computer models have been developed based upon the solutions of the heat and mass transfer equations. However, to date, satisfactory models do not exist that account for both the chemical reactions and the heat and mass transfer simultaneously. Although such models would be useful in predicting the effects of geothermal fluids on power plants and other operations prior to construction, they are difficult to develop because of the extreme chemical complexity of geothermal fluids from site to site. This is illustrated in Tables 8 and 9 (from Austin and Pringle, 1974). These analyses come from major geothermal fields of the world for both dry steam and hot water systems and show variations in pH from 1.8 to 8.6, while the total dissolved solids vary from approximately 400 at Larderello to almost 260,000 ppm at the Salton Sea.

Since each constituent in water has its own solubility characteristics as a function of pressure and temperature, almost every phase of power plant operation is influenced by one or more of the chemical constituents. In the Cerro Prieto and Wairakei fields the water in the well tends to flash to steam in the upper third of the well, causing precipitation scaling on the casing in the vicinity of the flashing. As these contaminants build up on the casing wall they tend to restrict the flow, thereby further reducing the pressure and increasing the rate of deposition. Somewhat similar scaling and precipitation problems occur in heat exchangers where rapid temperature changes are taking place. Furthermore, reinjection of cool, supersaturated geothermal fluids into the reservoir tends to plug the formation immediately around the well, thereby reducing permeability and restricting usefulness of the well. Furthermore, release of noncondensible gases, in particular hydrogen sulphide, into the atmosphere tends to corrode exposed metals and is often blamed for the failure of electrical apparatus in the immediate vicinity.

TABLE 8. Chemical Analyses of Waters Associated with Larderello, Wairakei and The Geysers Areas in ppm

Source: Austin and Pringle, 1974)

Location: Water Type: System Type:	Larderello, Italy[a] $SO_4HCO_3(Cl)$ hot water	Well #4 Wairakei, N.Z.[b] Cl hot water	Well #5 Wairakei, N.Z.[c] HCO_3-SO_4 vapor dominated (?)	The Geysers, Calif.[d] HCO_3-SO_4 vapor dominated	The Geysers, Calif.[e] Acid Sulfate vapor dominated
SiO_2	...	386	191	66	225
Al	Trace	...	...	...	14
Fe	Trace	...	...	...	63
Mn	...	...	...	...	1.4
As	...	...	...	...	...
Ca	...	26	12	58	47
Mg	5.0	< 0.1	1.7	108	281
Na	56.6	1,130	230	18	12
K	32.0	146	17	6	5
Li	...	12	1.2	...	...
NH_4	19.0	0.9	0.2	111	1,400
H	...	...	...	...	9.5
HCO_3	89.7	35	670	176	0
CO_3	...	0 (?)	...	...	...
SO_4	137.4	35	11	766	5,710
Cl	42.6	1,930	2.7	1.5	0.5
F	...	6.2	3.7	...	...
Br	...	...	...	...	...
NO_3	...	...	...	...	...
B	13.9	26	0.5	15	3.1
H_2S	...	1.1	0	0	...
Total Reported	396.2	3,750	1,140	1,330	7,770
pH	...	8.6	6.7	neutral	1.8+
Temperature, °C	300	228+	high	100	boiling (?)

[a]Deepest well of hot-water field on south border Larderello steam fields (Cataldi and others, 1969). Original analysis in ppm, supplied by R. Cataldi, 1970.

[b]Typical of shallow Wairakei system; 375 meters deep with maximum temperature of 245°C (Banwell and others, 1957). Analysis by Wilson; also contains 11 ppm free CO_2 (Wilson, 1955; quoted in White and others, 1963, p. F40).

[c]Western part of Wairakei field (Wilson, 1955, quoted in White and others, 1963, p. F47). Similar to some waters of vapor-dominated systems; 467 meters deep, maximum 217°C at 271 meters.

[d]Witches Cauldron, White and others, 1963, p. F47, modified from Allen and Day, 1927.

[e]Devils Kitchen, White and others, 1963, p. F46, modified from Allen and Day, 1927.

TABLE 9. Analyses of Fluid From Wells in the Salton-Mexicali Geothermal Province

Source: Austin and Pringle, 1974

	Salton Sea geothermal field		Cerro Prieto geothermal field	
	I.I.D. No. 1[a]	I.I.D. No. 2[b]	M-5[c]	M-8[c]
Sodium	50,400	53,000	5,820	6,100
Potassium	17,500	16,500	1,570	1,860
Lithium	215	210	19	17
Ribidium	135	70	...	...
Calcium	28,000	28,800	280	390
Magnesium	54	10	8	6
Stronium	400	440	...	...
Barium	235	250	...	...
Iron	2,290	2,000	0.2	...
Manganese	1,400	1,370	...	...
Zinc	540	500	...	...
Boron	390	390	9.1[c]	15[c]
Chlorine	155,000	155,000	10,420	11,750
Fluorine	15	...	...	...
Bromine	120	...	14.1	14.3
Iodine	18	...	3.1	3.2
Silica	400	400	740	770
Sulfate	5.4	...	0.0	0.0
Hydrogen sulfide	16	...[b]	700	...
Bicarbonate	> 150	690[b]	73	890
Carbon dioxide	...	...	1,600	...
Total as reported	258,973	259,000	19,018	21,915

[a]White, 1968, Table 1.

[b]Halgeson, 1968, Table 1; HCO_3 calculated from total CO_2 of 500 ppm; total sulfur given as 30 ppm.

[c]Spiewak, et al, 1970, Table II; boron calculated from H_3BO_4.

Field tests are being conducted at most geothermal sites to determine the most practical materials for plumbing and facilities. One example is the corrosion research work conducted by Austin and others at Coso Hot Springs on the Naval Weapons Center range at China Lake, California (Austin and Pringle, 1974; Finnegan, 1976; Ham, 1972). These researchers have been testing a variety of metals and nonmetal products over long-term exposures to geothermal fluids under field conditions. An analysis of the geothermal fluids at Coso is given in Table 10 and 11, where again very wide variation in pH is noted. Corrosion arrays have been set up by Naval Weapons Center to test samples under both oxygen poor (anaerobic) and oxygenated (aerobic) conditions within the sample pipes. A total of 20 ft of pipe is exposed under each condition. In other arrays, valves, tees, and other plumbing fixtures are also under test. Tests have included a variety of galvanized pipe, black iron pipe, copper pipe, PVC, transite, 6063 aluminum, stainless steel, ADS plastic, and a variety of other materials. The results are qualitative as the samples in the arrays have not been completely analyzed. However, visual estimates of the damage to a variety of the samples is given in Table 12. Some materials show little failure and even some relatively inexpensive materials, such as mild steel, show encouraging results. This research is continuing and is expected to yield more quantitative results during the next fiscal year.

TABLE 10. Analysis of Fluids and Alteration Products in the Coso Thermal Area

Source: Austin and Pringle, 1974

Analysis	Location						
	Devil's Kitchen, clear pool	Resort, shallow steam well	Resort, shallow well next to fault scarp	Resort, shallow well at old steam bath	Devil's Kitchen, siliceous residue	Devil's Kitchen, green siliceous residue	Resort, red mud
	% Residue on evaportation to dryness				% of sample		
Constituent:							
Si	10-100	10-100	10-100	10-100	10-100	10-100	10-100
Fe	...	3-30	3-30	3-30	.1-1	1-10	1-10
Al	1-10	1-10	1-10	3-30	1-10	3-30	3-30
Ca	.3-3	.1-1	.1-1	1-10	.03-.3	.01-.1	.1-1
Mg	.1-1	.3-3	.3-3	.3-3	.01-.1	.003-.03	.1-1
Na	.03-.3	.3-3	.1-1	1-10	.01-.1	.03-.3	.1-1
K	.3-3	.1-1	.1-1	3-30	...	.3-3	.3-3
Mo	...	.0003-.003	.0003-.003	...	...	...	...
Zn	...	.003-.03	.01-.1	...	...	...	...
Sn	...	...	...	.01-.1	.001-.01	.001-.01	.003-.03
Co	...	...	...	.001-.01	...	.0003-.003	...
Sc	...	...	...	.0003-.003	...	.0003-.003	.003-.03
Y	...	...	...	...	...	.001-.01	...
B	.3-3	.03-.3	...	.1-1	.01-.1	.003-.03	.001-.01
Mn	.003-.03	.03-.3	.03-.3	.1-1	.001-.01	.0003-.003	.003-.03
Ag	...	...	...	...	...	...	.0003-.003
Cu	.003-.03	.01-.1	.003-.03	.01-.1	.003-.03	.003-.03	.003-.03
Ti	.03-.3	.1-1	.1-1	.1-1	.1-1	.3-3	.3-3
Sr	.01-.1	.003-.03	.003-.03	.003-.03	.01-.1	.03-.3	.03-.3
Ni	.003-.03	.0003-.003	.0003-.003	.003-.03	.001-.01	.003-.003	.001-.01
V	.001-.01	.001-.01	.001-.01	.001-.01	.001-.01	.003-.03	.003-.03
Pb	.001-.01	.001-.01	.003-.03	.03-.3	.001-.01	.01-.1	.003-.03
Ba	.003-.03	.01-.1	.01-.1	.01-.1	.01-.1	.3-3	.03-.3
Ga	.001-.01	.001-.01	.001-.01	.001-.01	.0003-.003	.003-.03	.001-.01
Cr	.0003-.003	.0003-.003	.0003-.003	.001-.01	.0003-.003	.001-.01	.003-.03
Zr	.0003-.003	.003-.03	.003-.03	.003-.03	.01-.1	.03-.3	.003-.03
Be	.0003-.003	.001-.01	.0003-.003	...	...	...	...
Total dissolved solids, ppm	2,500	2,800	2,800	2,700	...	...	...
pH	1.5	4.5	4.5	...	...	...	...
Temp., °F	176	203	203	...	...	...	...

TABLE 11. Water Analysis of Samples From Coso No. 1 Drill Hole Taken at Depth of 375 Feet

Source: Austin and Pringle, 1974

Sample 1 was taken from the well discharge (clear water) at completion of drilling after blowing the well with compressed air for over 1 hour. Samples 2 and 3 were taken after the well was idle for 7 months. Sample 2 is from the first and third bailer, and Sample 3 from the 13th and 14th bailer.

Data	Sample No. 1	2	3
Data:			
Sample taken	27 Jun. 67	Mar. 68	Mar. 68
Analysis	12 Jul. to 3 Aug. 67	16 Apr. 68	16 Apr. 68
Temp., °F	240	287	287
Constituent, ppm:			
Ca	72.8	359.0	74.4
Mg	0.5	0.6	1.0
Na	1,764	2,808.0	1,632.0
K	154	172.0	244.0
Co_3	84	50.4	77.4
HCO_3	134.2	0.0	0.0
SO_4	38	216.0	52.8
Cl	2,790	3,681.0	3,042.0
NO_3	7.1	trace	trace
NO_2	...	negative	negative
SiO_2	50	27.0	154.0
F	3.70	1.60	2.20
B	48	57.42	71.60
Fe	0.15	...	...
Mn	0.0	...	...
PO_4	0.4[a]	0.23	0.88
Cu	0.0	...	...
OH	...	76.2	1.7
Br	...	4.67	2.55
As	...	0.94	7.50
NH_4	...	trace	trace
Hg	...	1.4	0.0
Synthetic detergents, apparent ABS	0.290	...	...
Total dissolved solids, ppm	5,744	6,894.0	5,228.0
pH	8.9	9.8	8.5
Analytical laboratory	Navy	Hornkohl	Hornkohl

[a] Ortho.

TABLE 12. Materials Tested by Thirty-Day Immersion in the Coso No. 1 Well
Source: Austin and Pringle, 1974

Material	Obvious rapid failure	Obvious slow failure	No obvious chemical failure
Nylon rope	X		
Hemp rope	X		
305 Stainless		X	
304 Stainless			X
Monel		X	
Ni resist		X	
Mild steel		X	
Fiberglass (copper-loaded)			X
Epoxy-coated shaft	X		
Delrin 9D9		X	
Polyphenylene sulfide		X	
Polyethylene			X
Lexan polycarbonate		X (but extensive scaling)	
Neoprene jacketed wire			X
Lead jacketed wire			X
Kynar insulated wire			X
Hypalon insulated wire		X	

Environmental Impacts

Waste Water

Use or disposal of waste water (water from the well) is a significant potential environmental impact of a geothermal electric power plant. The impact depends on the type of geothermal reservoir and is minimal for a dry steam system such as at The Geysers in California. First, because the heat transfer material at the surface is dry steam, little waste water is produced. Second, underground fractional distillation of the steam leaves the majority of dissolved minerals in the earth. Water condensate remaining after passing the well steam through turbines and evaporators will contain traces of chemicals which could cause adverse environmental impacts if the water were discharged directly into local streams. Thus, further water treatment may be necessary or, as at The Geysers, the water may be injected into the ground via deep wells.

The impact is greater for wet steam or hot water geothermal systems. In these systems the amount of waste water is greater per megawatt than for dry steam systems, and the mineral content can be greater because of larger water volume and greater concentration. In such systems, water may make up 2/3 to 4/5 of the well fluid and must be separated from the steam. At Cerro Prieto, Mexico, the waste water contains about 2% salt--compared to 3.3% for ocean water. A geothermal electric power plant of 1000 MW would produce about 150 million gallons per day of brine and 12,000 tons of salts per day. This problem has received initial study for the Salton Sea area where the percent of salt is 20% (California DWR Bulletin 143-7, 1970). Injection wells appear the most promising solution to the salt problem.

A sound injection technology would eliminate the major portion of the environmental problems. It should be given high R&D priority and should underlie the geothermal energy environmental control strategy. Surface disposal of waste water should also be considered when compatible with environmental standards because it may provide valuable supplies of water and minerals and may be necessary if injection cannot be used.

One of the most complete references on the general topic of environmental effects of geothermal energy was prepared by the Department of Interior in a four volume series. It is the environmental statement for the geothermal leasing program (U.S. Department of Interior EIS, 1973).

A 1000 MW geothermal electric power plant operating with 20% efficiency would reject 4000 MW. This compares to a nuclear power plant with a 33% efficiency which would reject 2000 MW of heat. Geothermal electric power plants with 20% efficiency and water tower-cooled condensers would be typical for dry steam systems, while wet steam fields can have heat rejection rates several times greater. Efficiency of a plant would drop if dry cooling is used. Considering the efficiencies and typical cooling tower performance, up to 50,000 acre ft/yr of cooling water would be evaporated by a 1000 MW electric power plant.

Air Pollution

Geothermal wells often bring to the surface noxious gases. Hydrogen sulfide, H_2S, presents the significant environmental problem. Carbon dioxide and other gases are also present in geothermal steam. Noncondensable gases average 1% of the steam flow at The Geysers. Of this 1%, 79% is CO_2, 5% methane, 1% hydrogen, 3% inerts, 5% H_2S, and 7% ammonia. These numbers for The Geysers show that H_2S is present in the steam with a concentration of 225 ppm. Humans detect the odor at only 0.020 ppm. Irritation occurs in the 10 to 20 ppm range, and 225 ppm can be harmful with exposures of 1 hour or more. However, the H_2S at The Geysers is dissipated from tall stacks and ground level concentrations are low.

At the Cerro Prieto geothermal power plant, located in northwestern Mexico, hot brine and steam are separated at the wellhead and the brine is discharged to a pond. The steam and noncondensable gases (rich in CO_2 and H_2S) pass through a turbine, condenser and then enter a cooling tower. The concentration of total Hg in noncondensable gases ranged from 210-340 ng/ℓ; cooling tower air averaged 0.56 ng/ℓ; and steam condensate averaged 5200 ng/ℓ. The majority of the volatile Hg is present as Hg^0 (elemental vapor). A

mass balance for Hg in the power plant indicated that 90% of the Hg entering the plant was released to the environment in the cooling tower air at a rate of 5.4 g/hr, much less than the 100 g/hr allowed by EPA for smelters. Because arsenic is present, mainly in the liquid phase, 99% of the As in the well water was separated from the steam and was discharged to the brine evaporation pond at a rate of 2480 g/hr. Both As^{+3} and As^{+5} were present in all the water samples. Hydrogen sulfide was released from the plant, mainly with the noncondensable gas, at a rate of 140 Kg/hr, which is comparable to the sulfur emissions (mostly SO_2) from a similar capacity coal-fired plant (Crecelius, et al., 1976).

In addition to H_2S, other entrained gases and minerals may cause an environmental impact. Some of these might be Radon-222, Lead-210, ammonia, boron, heavy metals, and fluorides. The degree of impact of any of these contaminants will be heavily site-dependent and will have to be treated on a site-by-site basis. In general, procedures can be implemented to remove any significant environmental impact from such materials.

Subsidence

Withdrawal of water from underground reservoirs may cause subsidence (land sinkage) under certain geologic conditions. Subsidence, being dependent on the local geological formations, will be site-dependent. Subsidence of about 4 m has occurred at the Wairkei, New Zealand field, but no known subsidence has occurred at The Geysers field. Waste water injection could mitigate any tendency for subsidence. In general it is felt that subsidence will not be a common concern in western U.S. geothermal developments, but each site should be mathematically modelled and carefully monitored. It is expected to occur in the Gulf Coast geopressured regions and control procedures will be needed.

Seismic

Seismic activity is likely in geothermal areas. Interpore water content in fault zones is thought to be an important seismicity factor. Thus, withdrawal or injection under pressure of massive quantities of water could affect seismic events. Whether this relationship is significant or not and

whether the effect is beneficial or detrimental to the environment is not known. However, only microseismic events, well below the level of human detection, have ever been related to power plant operation at any of the world-wide geothermal plants.

Noise

The major noise problems associated with geothermal energy generating systems are being solved. High levels of high frequency noise are generated by the steam emanating from the bore holes. The technology of silencers and mufflers has provided the necessary solutions. Occasional periods (like some types of maintenance periods) of high noise may occur in these steam fields but the environmental impact would be small.

Well Blowout

Geothermal reservoir pressures range from slightly above to below hydrostatic pressure except for geopressure reservoirs. Thus the probability of a well blowout is minimal for all but geopressure sources. The environmental impact of a blowout could be significant to land, water, and air. For example, if the geothermal source were a wet steam system, a blowout could release large quantities of brine. Since adequate casing and wellhead programs can prevent blowouts, even in geopressure regions, prevention can be considered a regulatory problem and not an environmental problem. The development of the geopressure resources will require strict attention to blowout prevention procedures.

Land Use

An environmental impact of geothermal energy utilization is the use of land. An upper estimate of the land required for 20,000 MW of installed capacity is 100,000 acres. The impact of land use as differentiated from other impacts discussed in this section stems directly from the intrusion of an industrial operation into an area. The geothermal system introduces noise, buildings, pipelines, cooling towers, drill rigs, and access roads.

Only a small part of the whole bore field is required for the wells, pipelines, and electric power generating plants. The rest could be used for other purposes. For example, at the Larderello field in Italy, where

geothermal steam has been used for electric power production for nearly 60 years, an intensive agricultural industry is carred on within the steam field, and many vineyards and orchards are interspersed among the pipeline and wells.

Nevertheless, some of the areas that will be considered for geothermal plants occur in places that are valued for their recreational and/or scenic value. Industrial plants in such areas would be incompatible with those values.

3. TECHNOLOGY UTILIZATION AND TECHNICAL INFORMATION TRANSFER

Our review of the ARPA research program in geothermal energy was based upon the eight reports submitted. We also studied a report by Combs, et al., (1976) as a direct continuation of the work under review. These nine are listed in the references section under the title, "References Reviewed by Contract." Thirteen additional references were reviewed because of their direct relationship to the ARPA Project and are listed in the section, "Other References." Also, a limited bibliography, which may be of interest to other reviewers, has been added. Review of the ARPA funded project shows the following results:

- A thorough overview of geothermal energy technology has been completed and will serve as a useful guide to program planners and managers (Stevovich, 1973).
- Particular DOD establishments where geothermal energy probably can be applied have been identified and target sites for initial projects are proposed (Combs, 1973; Herrin, 1973).
- Partly as an outgrowth of the ARPA funded project, one target site is under active exploration at the Naval Weapons Center at China Lake, California. The Coso Geothermal Project is proceeding with the geophysical surveys, geochemical studies, and exploratory drilling (Combs, 1975; Combs, et al., 1976; Finnegan, 1976).
- Certain key factors which will ultimately inhibit the development of geothermal energy without additional R&D have been identified. Problems of geothermal fluids chemistry and effects of corrosion, erosion, scaling and precipitation have been discussed. Field tests with geothermal fluids on selected materials have been carried out (Austin, Pringle, 1974; Finnegan, 1976).
- Another important factor affecting the economics of geothermal energy development is drilling technology. The high costs of drilling and

technological limitations of working in high temperatures are limitations that have been addressed. Some solutions have been proposed but, in general, significant R&D will be required (Patterson, Sabels, Kooharian, 1973).

- Selected topics associated with the environmental impact of geothermal energy were addressed by particular authors but not completely developed. However, an environmental statement was prepared by the Department of the Interior (1973) which has been reviewed.

Follow-on work toward the development of geothermal energy is being conducted by ERDA, USGS, the Naval Weapons Center, and other government agencies. Since many programs under these agencies were concurrent with the ARPA research program, it is difficult to measure the amount of technical information transferred among the various researchers. However, we found that, in the cases of geopressured systems and the project at Coso, technical information developed under the ARPA programs was being used by the research teams sponsored by other government agencies. In addition, one of the sites identified under ARPA sponsorship is actively being developed. Based upon this evidence alone it is evident that the ARPA sponsored research has had an impact and ultimately will help reduce the nation's dependence on foreign energy sources.

Additional research and development is needed relating specifically to DOD needs. Because military establishments are essentially controlled communities, utilization of geothermal energy for nonelectric applications (heating, refrigeration, air field and harbor de-icing, chemical processing, etc.) can probably be explored and developed more effectively than in other areas of the American economy. Many DOD sites have been identified where such development is possible. Additional research is needed on the chemistry of geothermal fluids at specific DOD sites. Development, either for electric or nonelectric applications, cannot proceed without thorough knowledge of this subject. At certain DOD sites it is highly probable that electric power generation is possible from known geothermal resources. Such development should be pursued to reduce DOD dependence on oil and oil supply lines.

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ARPA FUNDING SUMMARY

	FY73	FY74
Informatics, Inc. Rockville, Maryland		
Naval Weapons Center China Lake, California		60.0K
Southern Methodist University Dallas, Texas	17.0K	
Tetra Tech, Inc. Houston, Texas	55.0K	
University of California Riverside, California	33.0K	65.7K

COMMENT ON MANAGEMENT

Although it is difficult to evaluate the management of projects from a distance, a number of comments may be appropriate with respect to the end result, namely the reports produced. The reports prepared by Austin and Pringle (1974) and Finnegan (1976) are concerned with the chemistry of geothermal fluids and, in particular, with those at the Coso Geothermal Site. Exposure of materials to fluids began in 1973 or earlier, and significant and important data have been gathered. These researchers should be encouraged to publish their reports in that their ongoing research would be valuable to others.

The work by Combs and others at the Coso Geothermal Site should be singled out as a good example of cooperation among government agencies to fund and develop a national resource over an extended period of time. Current reports of this work are available from Battelle-Northwest.

The work by Herrin surveyed geopressured reservoirs starting from the geological and geophysical phenomena and following through with proposed sites for development. A fairly thorough environmental analysis for the specific sites was also completed.

The work on ultra-deep drilling by Patterson et al., (1973) summarizes current drilling technology and problems and identifies the boundaries and limitations currently being encountered. It does not tell of research in foreign countries, some of which is at the forefront of technology, but it does outline directions which research should take. Significant additional research on this topic is required.

The overview of geothermal energy by Stevovich (1975) summarizes the engineering technology of geothermal energy. The sections on activities in foreign countries is particularly valuable and has collected in one spot information difficult to obtain. It does not deal heavily with the problems associated with exploration geology and geophysics, nor with environmental issues, but such information is readily available from other U.S. sources. The work will serve as a reference source for researchers and managers.